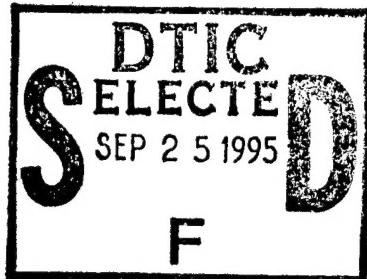


CBBL-SRP FINAL REPORT, FY 1993-1994

Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure



Charles A. Nittrouer

Glenn R. Lopez

Marine Sciences Research Center

**State University of New York
Stony Brook, NY 11794-500**

19950921 008

INTRODUCTION

This document is the final summary report for research conducted under Naval Research Laboratory (NRL) parent grant N00014-93-1-6004, "Physical and biological mechanisms influencing the development and evolution of sedimentary structure," funded through the Coastal Benthic Boundary Layer Special Research Program during fiscal years 1993 and 1994.

We participated in three research cruises in winter and spring 1993, and one in summer 1994; analyses were carried out through 1993 and 1994, and results presented in 1994 and 1995. The description of methods, results, and discussion in this report reflects that chronology.

GENERAL SUMMARY OF WORK DURING THE FIRST YEAR

Research work completed during 1993 included the collection of samples in Eckernfoerde Bucht and the beginning of laboratory analyses for those samples. During March-May 1993, we participated in three cruises. The sample sites were concentrated at the deployment locations of acoustic and boundary-layer towers, as well as positions farther northeastward and southwestward within the bay (Fig. 1). Replicate cores (4-7) were collected at 14 stations, and many of the stations were reoccupied on different cruises (Table 1). Some of our sample processing was completed in the field, but most awaited the return of samples to our laboratory.

They were returned to the US in August, and analyses of sedimentological, radiochemical and biological properties were begun.

Our work has been coordinated with the dynamical boundary-layer measurements of our co-PI, Don Wright and his research group at VIMS, as well as the acoustical observations of Darrell Jackson and his research group at University of Washington. The combined results are providing an understanding of physical and biological reworking for the seabed in Eckernfoerde Bay, and how this has affected sedimentological characteristics and the resultant acoustical properties.

Sedimentary structure in Eckernfoerde Bay is generally characterized by physical laminations, although biogenic mottling is present and becomes more common northeastward (toward the mouth). The benthos consist of an opportunistic community dominated by spionid polychaetes and tellinid bivalves, both surface deposit feeders. Profiles of ^{234}Th demonstrate that the community mixing depth is 1 cm or less. This observation combined with a relatively rapid accumulation rate ($>3 \text{ mm y}^{-1}$) allows many physical laminae to pass through the surface mixed layer intact, and to be preserved in the underlying portions of the seabed.

Description of Coring Stations

Most of the cores were collected at locations where the APL tower and the VIMS tetrapod were deployed, as shown below (Figure 1, Table 1).

Table 1. Station locations.

	<u>Cruise Number</u>		
	<u>BS-1</u>	<u>BS-2</u>	<u>BS-3</u>
APL/VIMS deployment site March-April	stations A,B,C,D,E,F	stations D,F	station D
APL/VIMS deployment site April-May	none	stations N,O,P	stations N,O

Two locations near Mittelgrund contained glacial sand and pebbles, and had a more diverse benthic community. The location at the west end of Eckernfoerde (near the Navy Base) had a large contribution of transported debris (sand, twigs, leaves, eel grass).

Dist		d / or Special
A-1		
Codes		
.....		
.....		
.....		
.....		

Sedimentological and Radiochemical Sampling

Cores were examined by observations of X-radiographs, microfabric, grain size, ^{234}Th , and ^{210}Pb . Slabs for X-radiography were obtained by pushing three-sided acrylic trays (2.5 x 15 cm cross-section) into core boxes on deck, then inserting the fourth side, so as to minimize fabric distortion (Kuehl and others, 1985). Slabs were fixed with formalin, sealed, and X-rayed aboard ship. Microfabric subsamples were obtained from X-ray slabs, and prepared using resin impregnation and petrographic thin-sectioning (Kuehl and others, 1988). Subsamples for grain-size measurement were disaggregated with 30% H_2O_2 (also removing organic matter; Ingram, 1971). Granulometric measurements were made with a Micromeritics ET-5100 Sedigraph following the methods of Coakley and Syvitski (1991), and were cross-checked with standard sieve, pipette, and settling-column techniques. ^{234}Th activities ($t_{1/2} = 24$ days) in the upper 10 cm were determined by γ -spectroscopy (63 keV peak: Buesseler and others, 1992). ^{210}Pb activities were measured by wet chemical leaching of samples to extract the granddaughter ^{210}Po , which was then analyzed by α - spectroscopy (Nittrouer and others, 1979). Excess activities of ^{210}Pb and ^{234}Th were determined by comparison with supported background activities.

Benthic Biological Sampling

The benthos subsample cores were divided into 0-2 and 2-10 cm layers, and sieved through a 500 μm sieve. Animals collected on the sieve were then preserved in glass jars with 4% seawater formaldehyde and rose bengal. Animals were counted and identified to the lowest taxonomic unit.

A bioturbation experiment was established to compare vertical and horizontal particle bioturbation rates in a variety of sediments and faunal communities. Fifteen-cm diameter cores (see Table 2) were brought to shore and placed in a running seawater system. A 50-ml suspension of a second color of fluorescent particles (in seawater) was added to each core. These particles settled overnight onto the sediment surface.

Control cores were broken down during the following two days. There was one control core from each station. Nine to 12 subcores (small syringes) were taken from each control core. Each subcore was vertically sectioned at 7 depth intervals of 0-0.5, 0.5-1, 1-1.5, 1.5-2, 2-3, 3-4,

and 4-5 cm. Cores for porosity also were taken and divided in the same manner. Small x-ray slabs were obtained from each core.

Table 2. Description of samples for bioturbation experiment

Date sampled	Station	Box core #	Comments	Transition Site
27 April 93	I	106, A, B 107, C, D	4 small box cores	
28 April 93	D	119 A-C	Large box core	Old Tower Site
28 April 93	H	114 A-D	Large box core	Navy Base Site
28 April 93	N	128 A-D	Large box core	New Tower Site
29 April 93	O	143 A-C	Large box core	New Tower Site
29 April 93	G	146 A, B 147 C	Small box core	Mittelgrund Site
29 April 93	F	151 A-D	Large box core	Old Tower Site

Table 3. Station locations and core subsamples, BS4.

Station	Sample Type	Date/Time	Location ¹	Latitude N	Longitude E	Water Depth	Subsampling ²
602	Box core	06/27/94 14:45	N	54 23 43.9	09 59 31.0	25 m	XR, Pb, BIO
604	Gravity core	06/27/94 18:15	N	54 29 44.9	09 59 29.4	25 m	Pb
606	Gravity core	06/28/94 09:47	F	54 29 25.54	09 58 59.05	25.5 m	Pb
607	Gravity core	06/28/94 10:16	F	54 29 22.97	09 59 00.03	25.5	Pb
611	Box core	06/28/94 11:22	F	54 29 24.4	09 59 01.2	25 m	Pb, XR, C, BIO
620	Box core	06/29/94 10:41	HG	54 32 13.26	10 03 33.50	27 m	Pb, XR, BIO, C
621	Gravity core	06/29/94 11:16	HG	54 32 12.0	10 03 36.0	28 m	C, Pb
623	Gravity core	06/29/94 12:05	HG	54 32 12.3	10 03 29.1	28 m	C, Pb
630	Box core	06/30/94 08:31	TR	54 30 00.95	09 58 33.69	25 m	XR, BIO
631	Box core	06/30/94 08:51	TR	54 30 10.60	09 58 31.87	21 m	XR, BIO
633	Box core	06/30/94 09:11	TR	54 30 12.50	09 58 35.83	21 m	XR, BIO
635	Box core	07/01/94 09:17	TR	54 30 06.16	09 58 24.68	22 m	XR, BIO
636	Box core	07/01/94 09:32	TR	54 30 07.59	09 58 15.53	17 m	XR, BIO
637	Box core	07/01/94 09:53	TR	54 30 03.66	09 58 00.41	14 m	XR, BIO
648	Box core	07/02/94 am	F?	54 29 26.15	09 58 14.00	25 m	Th

¹N,F = APL tower sites; HG = Hausgarten; TR = transect stations.

²XR = X-ray slabs, also for microstructure; Pb = ²¹⁰Pb subsampling; C = ¹⁴C subsamples; BIO = fecal pellet and/or organism subsamples; Th = ²³⁴Th subsampling.

Salinity and temperature were monitored during the course of the experiment.

Experimental cores were incubated in the running seawater system for approximately 2 weeks, then were broken down in the same manner as the controls. After subcores were taken from the experimental cores, the remaining sediment (~70% of the total) was sieved through a 500-μm

sieve, and the animals collected were preserved for later enumeration. Fluorescence from sediment subsamples was extracted and measured by fluorometry.

SEDIMENTOLOGY AND RADIOCHEMISTRY

Summary of work

Sediment in the central basin of Eckernfoerde Bay is characterized by beds of clay-sized material, with slightly coarser laminations (~10% silt and sand). Excess ^{234}Th activity indicates that mixing is limited to the upper 8 mm of the seabed. Accumulation rates, measured by ^{210}Pb geochronology, range from 3 to over 11 mm yr^{-1} . The relatively high accumulation rates and absence of a significant mixed layer in the central bay allow fluctuations of sedimentological processes to be recorded in fine detail. Sediment-transport studies indicate that the laminated bedding is caused by alternating deposition of storm-suspended sediments from adjacent shallow-water areas and fair-weather supply of fine suspended material advected from the open Baltic.

X-radiography

X-radiographs of cores from the central basin of Eckernfoerde Bay show laminations in the upper 20-30 cm of the sea floor. The laminations are interbedded with thicker beds (several cm thick). Contacts between beds and laminations are diffuse. Laminations are generally more absorptive of X-rays than the thicker beds (thus appearing dark in positive prints: Fig. 2), and may be laterally discontinuous.

Microfabric

Two general types of microfabric were observed in cores from the central basin: pelletal fabrics (pellets > 10% of volume; percentages are approximate) and non-pelletal fabrics (pellets < 10% of volume). Of these, pelletal fabrics are by far the most common, and may be either matrix supported or pellet supported. Transitions from non-pelletal layers to overlying pelletal layers tend to be gradational, whereas contacts between non-pelletal and underlying pelletal layers are sharp (Fig. 3).

Pelletal fabrics tend to be anisotropic. Non-pelletal laminations sometimes display graded bedding (Fig. 3); other laminations may show no obvious grain-size variations between layers. In general, microstructural laminations correspond to laminations observed in X-radiographs, and pelletal fabrics in thin section are associated with thicker, homogenized beds seen in X-radiographs.

Grain-size distribution

Grain-size distributions tend to be polymodal, with the primary mode centered between 9.5 and 11.5 ϕ and a secondary mode, less than 10% by mass, centered between 3 and 6 ϕ (Fig. 4). Subtle coarsening in the median grain size of each mode is commonly associated with laminations observed in X-radiographs (Fig. 2), and non-pelletal, graded bedding in microfabric (Fig. 3). The coarsening associated with these laminations is accompanied by a 2-4% increase in the mass percentage of particles in the 3-6 ϕ size range.

Radiochemistry

Sediment accumulation rates in the central basin determined by ^{210}Pb geochronology range from 3 to over 11 mm per year (Fig. 5). Excess ^{210}Pb is present in the seabed to depths of 30-40 cm (Fig. 5). Excess ^{234}Th is restricted to the upper 5 mm of sediment, indicating that mixing is restricted to this thin veneer in the sea floor. No significant seasonal variability in sediment mixing depths was observed over winter, spring and summer cruises, although intensity may of mixing may change. Lateral variability of accumulation rates within the central basin was minimal.

Shallow penetration of sediment mixing results in the preservation of a detailed environmental record (cm-scale) in central-basin sediments. Long-term variations in ^{210}Pb profiles were observed in central-basin cores (Fig. 5), indicating historical shifts in either ^{210}Pb flux in coastal waters or changing sediment supply.

Sedimentary Event Layers

Once a sediment layer is deposited, it is then subject to modification by biological and physical mixing. In the absence of physical mixing, the degree of event-layer preservation in the

historical sedimentary record is a function of the deposited-layer thickness, the sediment accumulation rate, and the depth and rate of biological mixing (Guinasso and Schink, 1975; Nittrouer and Sternberg, 1981; Wheatcroft, 1990, 1994). Events layers thicker than the mixed layer can be generated by unusual events (from large storms or floods), and can overwhelm the benthos, interrupting biological mixing (Wheatcroft, 1994). (Biological mixing may be interrupted by other types of disturbances as well, such as anoxia, although the stratigraphic signature of temporary anoxia might be less obvious than a storm deposit.) The physical record of such an event would be a bed or lamination with a sharp lower boundary (resting on top of a bioturbated bed), a physically stratified lower layer, and a gradual increase upward in the intensity of bioturbation. This sequence has been widely recognized in coastal depositional environments (Frey and Howard, 1986; Leithold, 1989; Aigner and Reineck, 1982; Wheatcroft, 1994). The conceptual model is consistent with sedimentation in the central basin of Eckernfoerde Bay.

Depositional and Post-depositional Processes: Preserved Fabric

In order to assess the relationship between pulsed sediment deposition and rate of bioturbation, laminations were examined in thin section for evidence of progressive bioturbation with age. The laminations clearly preserved in thin sections (Fig. 3) have sharp lower contacts, and grade upward into progressively more pelletized sediment. This trend indicates that degree of pelletization can be used as an estimate of bioturbation intensity following event-layer deposition, when the pellets under study are resistant to breakdown. The thicknesses of unburrowed sediment in event layers are on the order of 3-5 mm, comparable to progressively pelletized layers. Each preserved lamination must have been initially thicker than the sediment mixing depth in the central basin, otherwise the lower boundary would not have been preserved.

Excess ^{234}Th activities (Fig. 5) were used to estimate the biodiffusion coefficient D_b ($\sim 0.3 \text{ cm}^2 \text{ yr}^{-1}$) in central basin sediments, using a solution to the steady-state advection/diffusion equation (Aller and Cochran, 1976),

$$D_b = \lambda(z/\ln(C_0/C_z))^2$$

where λ is the ^{234}Th decay constant (10.5 yr^{-1}), z is depth in the seabed (cm), C_0 is excess activity at the surface (decays per minute per gram of sediment: dpm/g), and C_z is excess activity at depth z (dpm/g). The thin surface mixed layer resulted in only two subsamples containing excess ^{234}Th

(Fig. 5). Because of the rapid mixing rates relative to accumulation rates, biological mixing is assumed to control the penetration of excess ^{234}Th into the seabed.

A method useful for assessing appropriate length and time scales of bioturbation is the decomposition of the biodiffusion coefficient into a mean step length and rest period (Wheatcroft and others, 1990) using the form $D_b = \delta^2/2\Omega$, where δ is mean step length, and Ω is mean rest period (yr). Assuming step lengths of 2 mm (appropriate to the benthic community, based on body length), the rest period is 24 days. To advect a 1 mm layer through the 5 mm mixed layer in less time than the rest period (and so preserve the layer) would require rapid deposition at rates equivalent to 7.5 cm yr^{-1} , one order of magnitude higher than the mean accumulation rates in the central basin ($\sim 7 \text{ mm yr}^{-1}$). Event layers exceeding the mixed-layer thickness satisfy these conditions.

Decadal-Scale Stratigraphic Record

Evidence of fluctuating accumulation rate is found on decadal scales, determined by ^{210}Pb geochronology (Fig. 5), as well as scales of single events, represented by non-pelletized laminations seen in thin sections (Fig. 4). Such fluctuations have been documented regionally (Balzer and others, 1986), and have been linked to winter-storm frequency and resultant resuspension and deposition (Khandriche et al, 1986). Shear velocities in the central basin have upper limits below critical erosion values (Friedrichs and Wright, in press), precluding significant physical sediment mixing. Biological mixing is seasonally intense, but is limited to depths ($\sim 8 \text{ mm}$) on the same order as annual accumulation rates ($3\text{--}11 \text{ mm yr}^{-1}$). Thus, upper sediments of the central basin preserve a relatively high-resolution historical record (cm-scale) of sedimentary processes.

Conclusions

The sedimentary input to the central basin is controlled by pulsed supply of fine particles from both proximal and distal sources. Time-series benthic-boundary-layer observations (Friedrichs and Wright, in press) indicate physical sediment mixing to be insignificant. Biological mixing is intense, but presently limited to the upper 8 mm of seabed. Sediment pulses (storm layers) exceeding the mixed-layer thickness may be preserved as individual laminations. Slower

deposition results in intensely reworked and pelletized sediment (pelletal fabric). Particle and chemical tracers reaching the seafloor may be vertically resolved to increments of ~5 mm, preserving a detailed stratigraphic record.

Fluctuations in the frequency of sediment pulses cause variations in ^{210}Pb accumulation rates (3-11 mm yr $^{-1}$). Similarly, sedimentary fabric (mm and cm scales) displays subtle gradients in grain size and bioturbation (including pelletization) that correlate to fluctuations in sediment supply rate.

BENTHIC BIOLOGY

Summary of work

The benthic macrofaunal community of Eckernfoerde Bay was characterized in terms of abundance and community structure. The community was dominated by small surface deposit-feeding animals. Faunal abundances in spring 1993 were 30,000-80,000 m⁻², and were 2,000-9,000 m⁻² in summer 1994. Particle bioturbation was limited to the top 0.5-1.0 cm throughout Eckernfoerde Bay. Functional group classification, faunal abundances, organism size, and particle bioturbation are consistent with the hypothesis that the benthic community of Eckernfoerde Bay is controlled by a regular disturbance which maintains the community at a low level of complexity. All measured biological components are consistent with sedimentological and radiochemical studies which indicate a thin layer (<1cm) of biological mixing.

Benthic Sampling

Benthic samples were taken during four ten-day cruises aboard the R.V. *Planet* and R.V. *Helmsand*, German naval research ships, during spring 1993 and summer 1994. Benthic sampling was focused around the acoustic tower deployment sites - Old Tower, New Tower - in the central basin (Fig. 5). Other samples were taken from the landward and seaward ends of the bay. These included both muddy sites - Eckernfoerde Navy Base, Stanic Tower, Hausgarten - and one sandy site, Mittelgrund. Three or more replicate box cores (20 x 30 x 50 cm) were collected per station. Three subcores were taken from each box core, were extruded, and divided into 0-2 and 2-10 cm sections. Animals were sieved from sediment using a 500-µm sieve and preserved. Animals were identified to the lowest possible taxonomic level (usually species). Each set of organisms was assigned to one of the following functional groups: surface deposit feeder, head-down deposit feeder, suspension feeder, or carnivore (see Table 4).

A bioturbation experiment was conducted to compare vertical particle mixing rates in different sediments and benthic communities. Three 15-cm diameter cores were collected from four stations along the axis of the bay - New Tower, Old Tower, Eckernfoerde Navy Base, Mittelgrund - in April 1993. Cores were maintained in a running seawater system at a shore lab, and subsampled as discussed previously. Samples were analyzed for fluorescence of tracer particles (modified from Carey, 1989). All values were corrected for background fluorescence.

Values from each depth interval were expressed as percent of the total fluorescence in that subcore.

Table 4. Rank order of dominant macrofauna in Eckernfoerde Bay.

<i>Polydora ciliata</i>	polychaete	surface deposit feeder/facultative suspension feeder
<i>Abra alba</i>	bivalve	surface deposit feeder/facultative suspension feeder
<i>Diastylus rathkei</i>	crustacean	surface deposit feeder
<i>Capitella</i> sp.	polychaete	small head-down deposit feeder
<i>Heteromastus filiformis</i>	polychaete	small head-down deposit feeder
<i>Pectinaria koreni</i>	polychaete	large head-down deposit feeder
tubificid sp.	oligochaete	large head-down deposit feeder
<i>Scoloplos armiger</i>	polychaete	large head-down deposit feeder
<i>Anaitides maculata</i>	polychaete	carnivore
syllid sp.	polychaete	carnivore
<i>Nephtys</i> sp.	polychaete	carnivore
<i>Harmat hoe</i> sp.	polychaete	carnivore
<i>Sigambra</i> sp.	polychaete	carnivore?scavenger
<i>Mytilus edulis</i>	bivalve	epifaunal suspension feeder
<i>Cerastoderma</i> sp.	bivalve	infaunal suspension feeder
<i>Corbula gibba</i>	bivalve	infaunal suspension feeder

Biological Observations

Macrofaunal abundance was high throughout the bay, dominated by small adults and juveniles of larger species. The dominant macrofauna consisted of 16 species (90% of total species) and 4 functional groups (Table 4). Benthic samples from the muddy stations - Old Tower, New Tower - in both 1993 and 1994 were dominated by small, numerous surface deposit feeders. The polychaete *Polydora ciliata* and the tellinid bivalve *Abra alba* accounted for 75-90% of all animals in many samples. Most of the *A. alba* were juveniles (<2.5 mm). Adult *Abra alba*

were absent but their characteristic fecal pellets were abundant in the central basin; their presence indicates lateral transport from the sides of the basin. The surface deposit feeding cumacean, *Diastylus rathkei*, was numerically important in the June 1994 samples.

Abundances of surface deposit feeders in March-May, 1993 samples (27,000 - 73,000 m⁻²) were significantly greater than the June-July, 1994 abundances (1,700 - 9,000 m⁻²) (Fig. 6). Decreases in abundance were coupled with a shift in community composition at the muddy stations (Tower stations, Navy Base, Transect Station A, Hausgarten). The relative abundance of surface deposit feeders at the tower stations decreased from 80-90% in March-May 1993 to 60-85% in June 1994 (Fig. 7). Carnivores, especially *Harmathoe* sp. were proportionally more important in the June 1994 samples. The relative abundances of head-down deposit feeders remained unchanged between the two sampling years.

Mittelgrund is a sandy site near the mouth of Eckernfoerde Bay (see Fig. 6). This area supported a distinctly different fauna with significantly lower abundances than the muddy stations in the central basin. Mittelgrund had more head-down deposit feeders and a higher proportion of carnivores than the Tower sites (Fig. 7). Suspension feeders were also significantly more abundant in the sandier site.

The results of the particle mixing experiments showed that fluorescent particles were mixed approximately 0.5-1.0 cm into the sediment for all sites over a two-week period (Fig. 8), regardless of functional group.

Our data indicates that the benthic fauna of Eckernfoerde Bay is dominated by small, surface deposit feeders, which do not mix particles deeply but probably mix the top cm of the sediment on short time scales (days). Differences in mean abundances between the two sampling years is thought to be seasonal (March-May in 1993 versus late June in 1994) and is consistent with previous work done in the Kiel Bight (e.g. Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

The abundances and composition of benthic fauna in Kiel Bight is strongly linked to seasonal patterns of oxygen availability in bottom waters (Kolmel 1979; 1977; Reimers; 1976). The benthic fauna of Kiel Bight typically experience an exponential increase in abundance, dominated by small, tube-building polychaetes such as *Polydora ciliata*, from March to early June followed by a crash in June-July (Weigelt 1991; Bosselman 1988; Meyer-Reil and others 1987;

Rumohr and Arntz 1982). In Eckernfoerde Bay, mean abundance of *P. ciliata* decreased an order of magnitude from the March-May 1993 sampling to the late June 1994 samples.

The primary controls on the benthic fauna of Eckernfoerde Bay during the study period were thought to be the rate of organic input to sediments, water-column stratification, deep-water mixing, and oxygen availability. During the spring bloom, carbon transport to the seafloor is between 10 and 15 g C m⁻² and one-third of the yearly organic input can reach the seafloor of the Kiel Bight in 1-2 weeks (Meyer-Reil and others 1987). Portions of the Kiel Bight, particularly the southwest portion where Eckernfoerde Bay is located, are annually subjected to periods of hypoxia and anoxia in summer due to stratification of the water column and stagnant physical conditions (Weigelt 1991; 1990; Meyer-Reil and others 1987). We hypothesize that the low oxygen conditions that occur with water column stratification in Eckernfoerde Bay causes a regular disturbance which controls the complexity of benthic community structure.

All measured components of Eckernfoerde Bay - abundance, diversity, animal size, functional groups, particle mixing - point to a community dominated by pioneering species (sensu Rhoads and Boyer 1982), especially *Polydora ciliata* and *Capitella* sp., and a system controlled by a regular or recent disturbance that reduced the complexity of the community structure and sediment reworking by the benthic fauna. This is borne out by our bioturbation experiments (Fig. 8), our sedimentology and radiochemistry results, and with numerous German studies of the Kiel Bight (e.g. Weigelt 1991, Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

REFERENCES

- Aigner T and Reineck H-E (1982) Proximity trends in modern storm sands from the Helgoland Bight and their implications for basin analysis. Senckenbergiana Maritima 14: 183-215
- Aller RC and Cochran JK (1976) ²³⁴Th- ²³⁸U disequilibrium and diagenetic time scales. Earth and Planetary Science Letters 29: 37-50
- Balzer W., Erlenkeuser H, Hartmann M, Muller PJ and Pollehne F (1986) Diagenesis and exchange process at the benthic boundary. In: Rumohr J, Walger E and Zeitschel B (Eds.), Lecture notes on coastal and estuarine studies, vol. 13: Seawater-sediment interactions in coastal waters. Berlin: Springer-Verlag, pp 111-161
- Bosselman A (1988) Settlement and succession of benthic animals - a subtidal experiment in the German Bight compared with the "Benthosgarten" experiment in Kiel Bay. Kieler Meeresforsch., Sonderh., 6:375-388

- Buesseler KO, Cochran JK, Bacon MP, Livingston HD, Casso SA, Hirschberg D, Hartman MC and Fleer AP (1992). Determination of thorium isotopes in seawater by non-destructive and radiochemical procedures. Deep-Sea Research 39: 1103-1114
- Carey D (1989) Fluorometric detection of tracer particles used to study animal-particle dynamics. Limnol. Oceanogr., 34(3): 630-635
- Coakley JP and Syvitski JPM (1991) Sedigraph technique. In: Syvitski JPM (Ed) Principles, methods, and application of particle size analysis. Cambridge: Cambridge University Press, 368 pp
- Frey RW and Howard JD (1986) Mesotidal estuarine sequences: a perspective from the Georgia Bight. Journal of Sedimentary Petrology 56: 911-924
- Friedrichs CT and Wright LD (in press) Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernfoerde Bay, Baltic Sea. Continental Shelf Research
- Guinasso NL and Schink DR (1975) Quantitative estimates of biological mixing rates in abyssal sediments. Journal of Geophysical Research 80: 3032-3043.
- Khandriche A, Werner F and Erlenkeuser F (1986) Effects of easterly storms of winter 1978/79 on the sediments of the Eckernfoerde Bucht, western Baltic. Meyniana 38: 125-152
- Kolmel R (1977) Okosysteme im Wechsel zur Anaerobiose. Zoobenthos und Abbau in zeitweise anoxischen Biotopen der Kieler Bucht.- Ph.D Thesis, Univ. Kiel and Rep. SFB 95 Univ. Kiel, 33, 403pp.
- Kolmel R (1979) The annual cycle of macrozoobenthos: its community structures under the influence of oxygen deficiency in the Western Baltic, p.19-28, In: E. Naylor and R.G. Hartnoll (eds.), Cyclic Phenomena in Marine Plants and Animals, Pergamon Press, Frankfurt.
- Kuehl SA, Nittrouer CA, DeMaster DJ and Curtin TB (1985) A long, square-barrel gravity corer for sedimentological and geochemical investigation pf fine-grained sediments. Marine Geology 62: 365-370
- Kuehl SA, Nittrouer CA and DeMaster DJ (1988) Microfabric study of fine-grained sediments: Observations from the Amazon subaqueous delta. Journal of Sedimentary Petrology 58:12-23
- Leithold EL (1989) Depositional processes on an ancient and modern muddy shelf, northern California. Sedimentology 36: 179-202
- Meyer-Reil L-A, Faubel A, Graf G, Thiel H (1987) Aspects of benthic community structure and metabolism, Ch. 3, p. 70-110. In: J. Rumohr, E. Walger, and B. Zeitzschel (eds.), Lecture Notes on Coastal and Estuarine Studies, Vol. 13, Seawater-Sediment Interactions in Coastal Waters.
- Nittrouer CA and Sternberg RW (1981) The formation of sedimentary strata in an allochthonous shelf environment: the Washington continental shelf. Marine Geology 42: 201-232
- Nittrouer CA, Sternberg RW, Carpenter R and Bennett JT (1979) The use of ^{210}Pb geochronology as a sedimentological tools: Application to the Washington continental shelf. Mar. Geol., 31, 297-316.
- Reimers T (1976) Anoxische Lebensräume: Struktur und Entwicklung der Microbiozonose an der Grenzfläche Meer/Meeresboden. Ph.D. Thesis and Rep. SFB 95 Univ. Kiel, 20, 134pp.
- Rhoads D and Boyer L (1982) The effects of marine benthos on physical properties of sediments: a successional perspective, Ch.1, p. 3-52. In: P. McCall and J. Tevesz (eds.), Animal-

- Sediment Relationships: The Biogenic Alteration of Sediments, Plenum Press, New York, Vol. 2, Topics in Geobiology.
- Rumohr H and Arntz W (1982) The "Benthosgarten" : a new approach for the study of soft-bottom communities. *Meeresforsch.*, 29(4): 225-238.
- Weigelt M (1990). Oxygen conditions in deepwater of Kiel Bay and the impact of inflowing salt-rich Kattegat-Water. *Meeresforsch.*, 33:1-22.
- Weigelt M (1991) Short- and long-term changes in the benthic community of the deeper parts of Kiel Bay (Western Baltic) due to oxygen depletion and eutrophication. *Meeresforschung*, 33:197-224.
- Wheatcroft RA (1990) Preservation potential of sedimentary event layers. *Geology* 18: 843-845
- Wheatcroft RA (1994) Spatial autocorrelation of mud-sand bed contacts in shelf environments. *Eos* 75: 203
- Wheatcroft RA, Jumars PA, Smith CR and Nowell ARM (1990) A mechanistic view of the particulate biodiffusion coefficient: step lengths, rest periods, and transport directions. *Journal of Marine Research* 48: 177-207

PUBLICATIONS AND PRESENTATIONS TO DATE

- Bentley SJ, Nittrouer CA and Lopez GR (1995) Measurement of progressive bioturbation in event layers, Eckernfoerde Bay, southwestern Baltic Sea. Proceedings of the FWG/NRL Workshop: Modelling Methane-Rich Sediments of Eckernfoerde Bay.
- Bentley SJ, Nittrouer CA and Sommerfield CA. Development of sedimentary strata in Eckernfoerde Bay, southwestern Baltic Sea. Submitted to Geo-Marine Letters
- D'Andrea AF, Lopez GR and Craig NI. Benthic macrofauna and bioturbation in Eckernfoerde Bay, Southwestern Baltic Sea. Submitted to Geo-Marine Letters
- D'Andrea AF, Lopez GR, Nittrouer CA and Wright LD (1995). Fecal pellets of *Abra alba* as tracers of sediment movement in Eckernfoerde Bay. Proceedings of the FWG/NRL Workshop: Modelling Methane-Rich Sediments of Eckernfoerde Bay.
- Lopez GR, Craig NI, Wallace WG (1994). Benthic faunal distribution and sediment bioturbation in Eckernfoerde Bay. *Eos* 75: 180
- Lopez GR, D'Andrea AF, Craig NI, Bentley SJ and Nittrouer CA (1995). Benthic macrofauna and bioturbation in Eckernfoerde Bay. Proceedings of the FWG/NRL Workshop: Modelling Methane-Rich Sediments of Eckernfoerde Bay.
- Nittrouer CA, Bentley SJ, Lopez GR and Wright LD (1995). Observations of sedimentary character and their relationship to environmental processes in Eckernfoerde Bay. Proceedings of the FWG/NRL Workshop: Modelling Methane-Rich Sediments of Eckernfoerde Bay.
- Nittrouer CA, Sommerfield CK and Bentley SJ (1994). Formation of sedimentary strata in Eckernfoerde Bay. *Eos* 75: 180

FIGURES

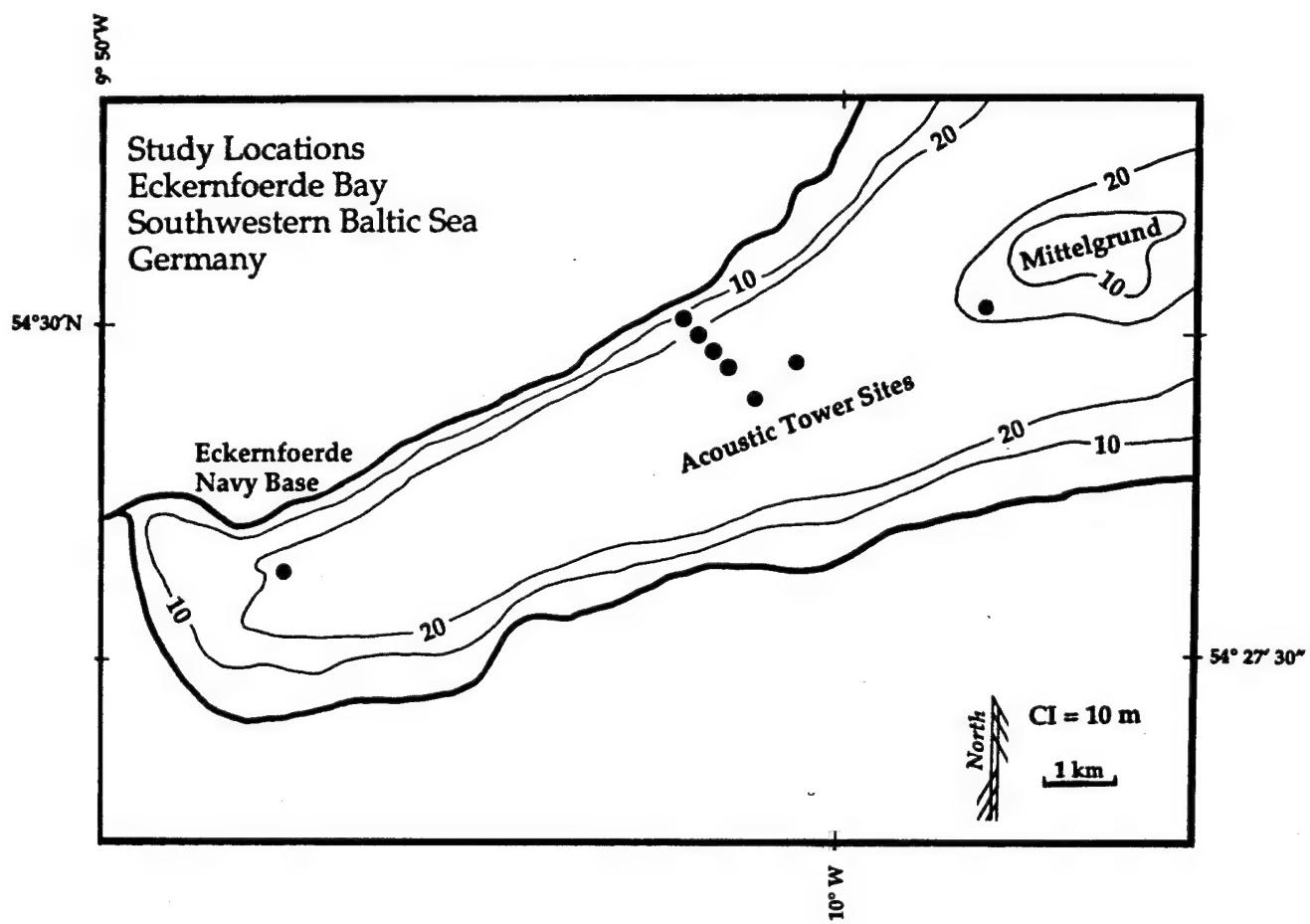


Figure 1 Map of coring locations in Eckernfoerde Bay.

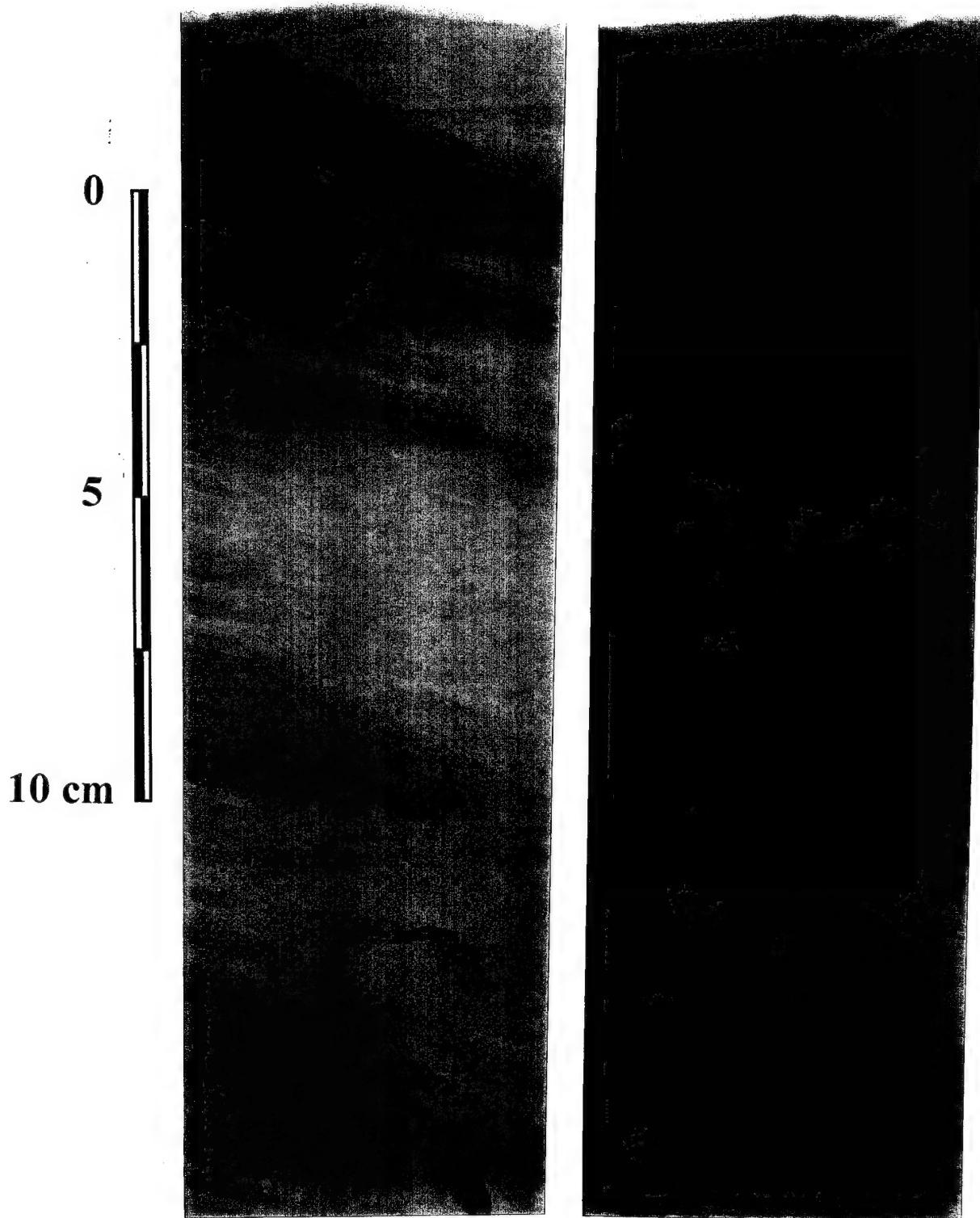


Figure 2 X-radiograph positives, BS4-611 (A) and BS4-602 (B). Stations were separated by ~1 km. Note darker laminations (non-pelletized event layers). Thicker, light-shaded beds are intensely pelletized.

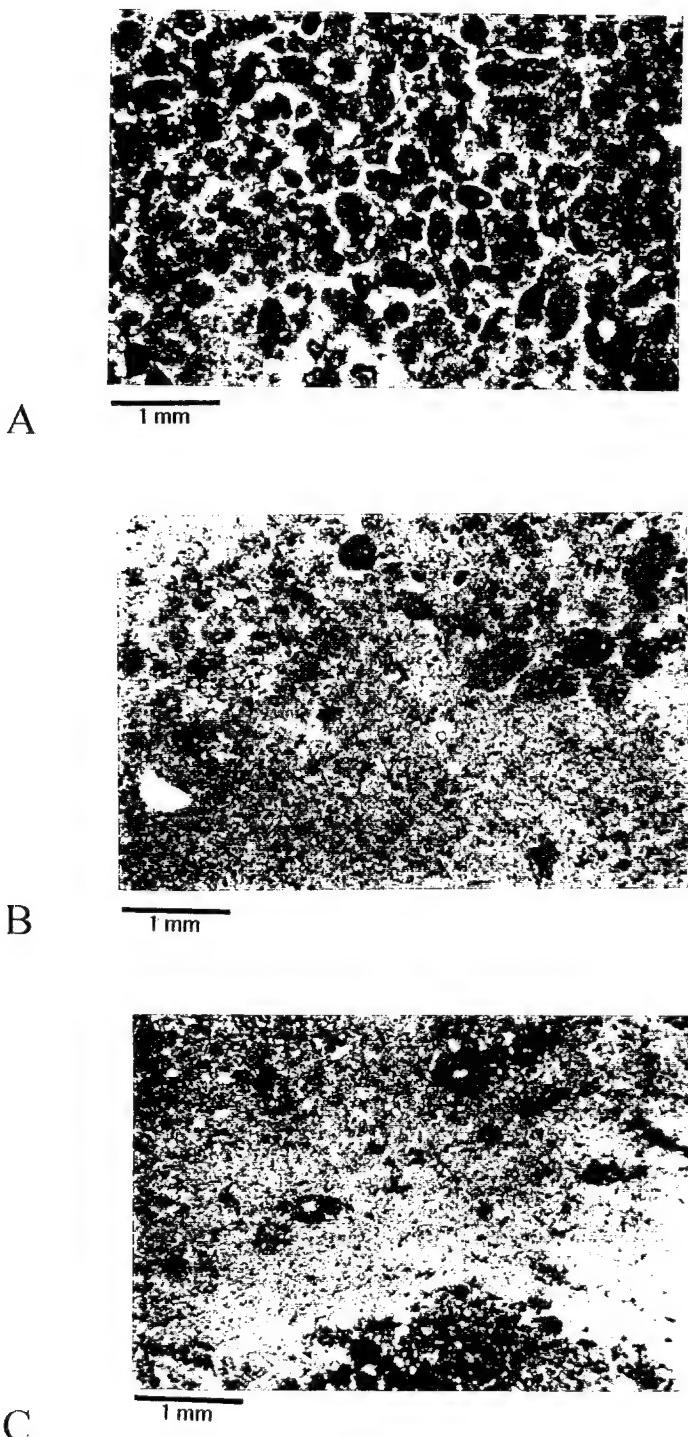


Figure 3 Figure 3 Photomicrographs, BS4-602. Field of view is 5.5 mm wide. A) 2.5-2.8 cm depth, plane light: intensely pelletized horizon; fecal pellets produced by the surface-deposit-feeding bivalve *A. alba* B); 6.7-7.0 cm depth, crossed polars: upper portion of event layer showing transition from non-pelletized (lower) to pelletized fabric (upper); C) 7.0-7.3 cm depth, crossed polars: basal contact between non-pelletized event layer and underlying pelletized horizon

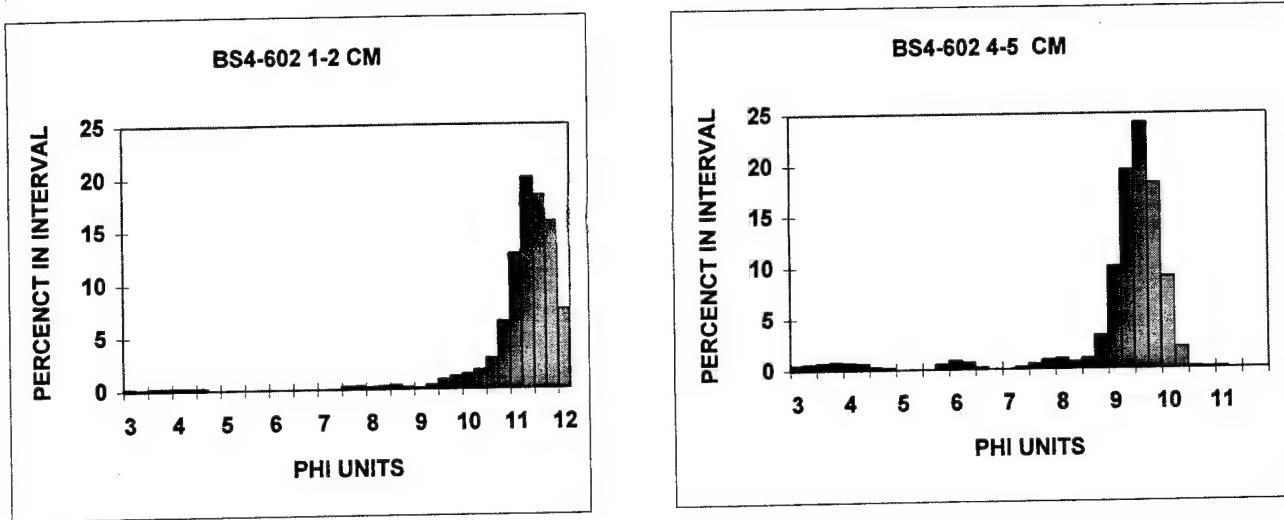


Figure 4 Grain size distributions BS4-602, 1-2 cm; and BS4-602, 3-4 cm. The 1-2 cm interval is characteristic of pelletized intervals, and the 3-4 cm interval, slightly coarser, is characteristic of non-pelletized event layers.

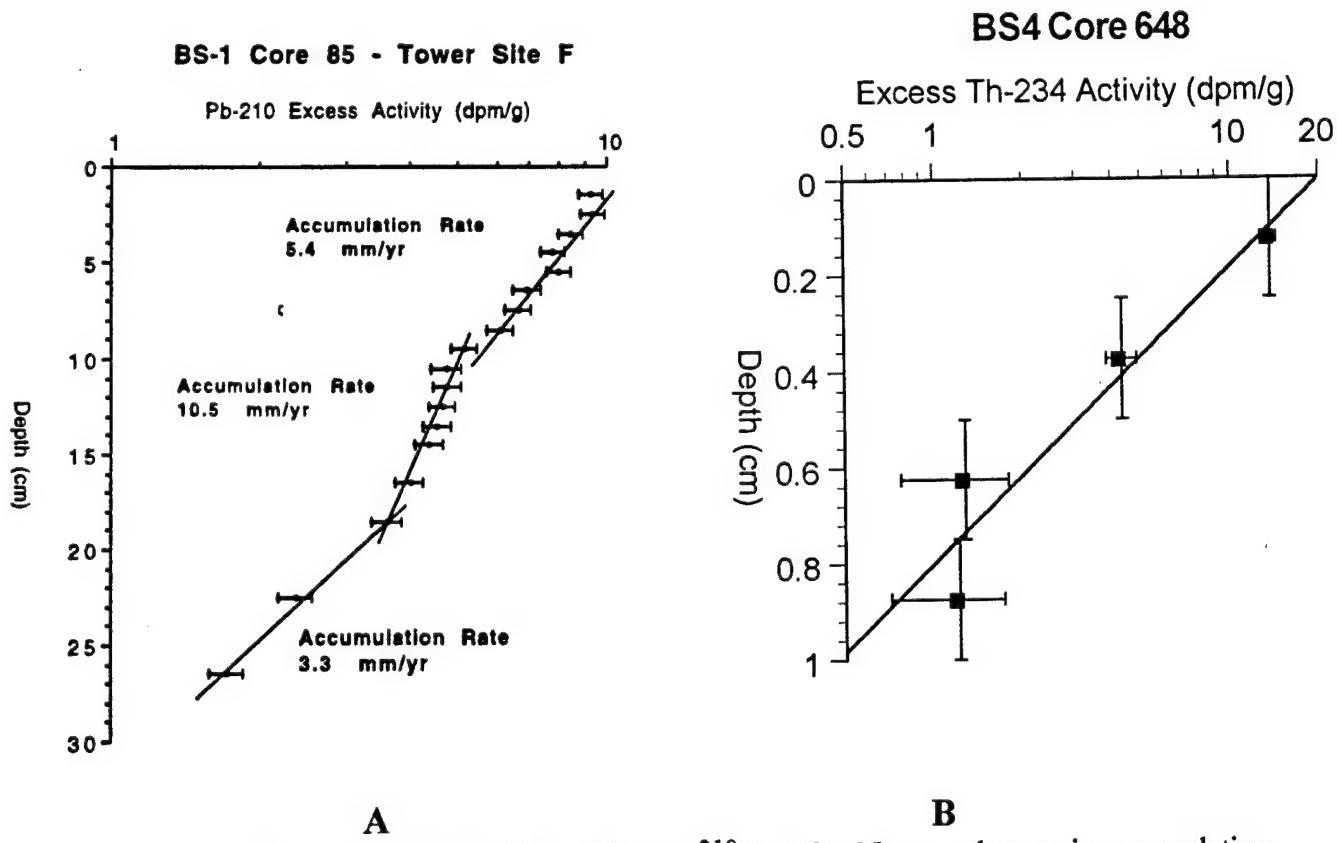


Figure 5 Radiochemical profiles. A)Excess ^{210}Pb , BS1-85, note changes in accumulation rate through time; B) excess ^{234}Th , BS4-648, excess activities are restricted to the upper 9 mm.

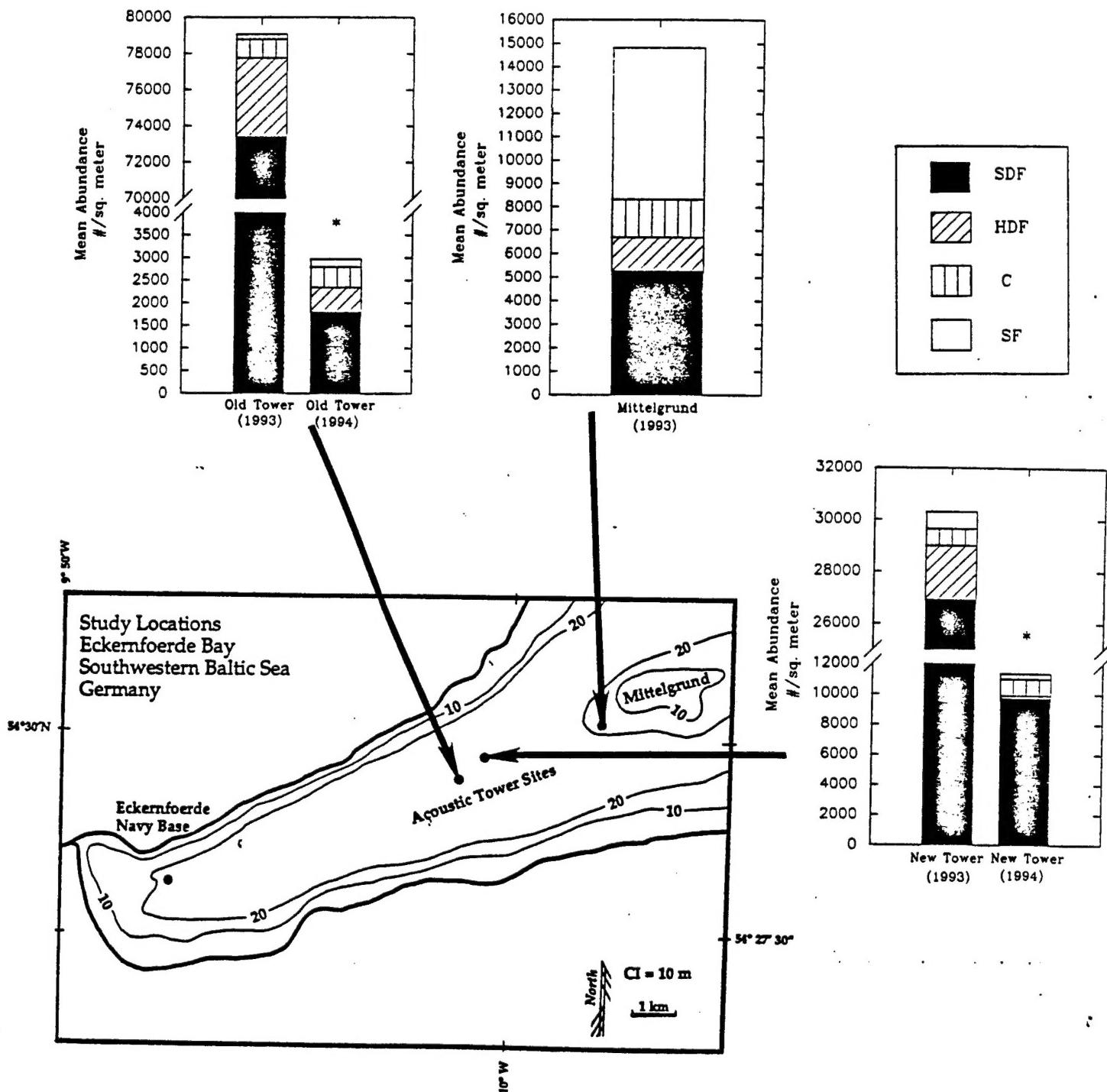


Figure 6. Mean Abundances at Primary Study Sites, 1993: mean from three cruises in Spring, 1993, 1994: mean from one cruise in Summer, 1994. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers. * = significantly different abundances than 1993 samples ($\alpha=0.05$).

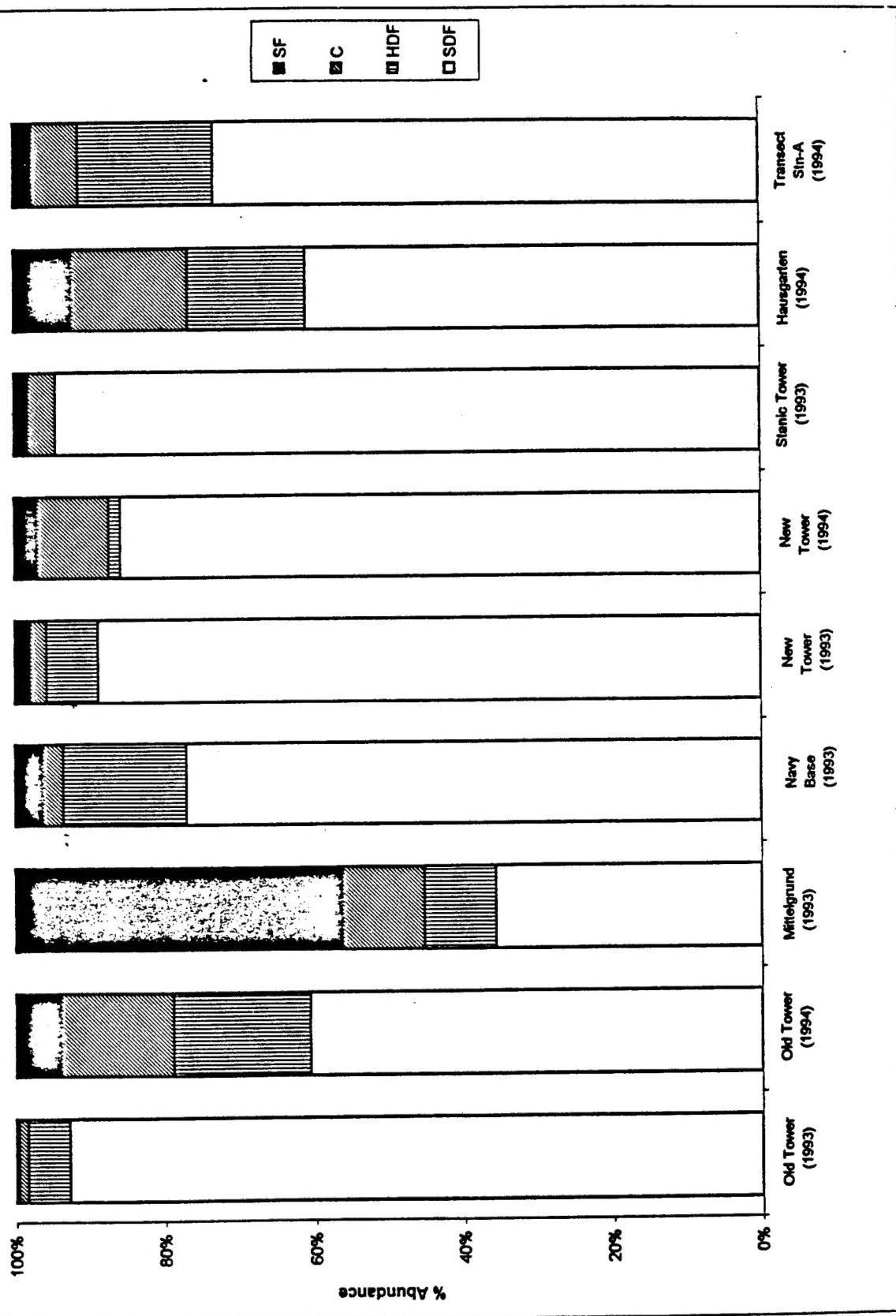


Figure 7. Percent Composition of Functional Groups by Station. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers.

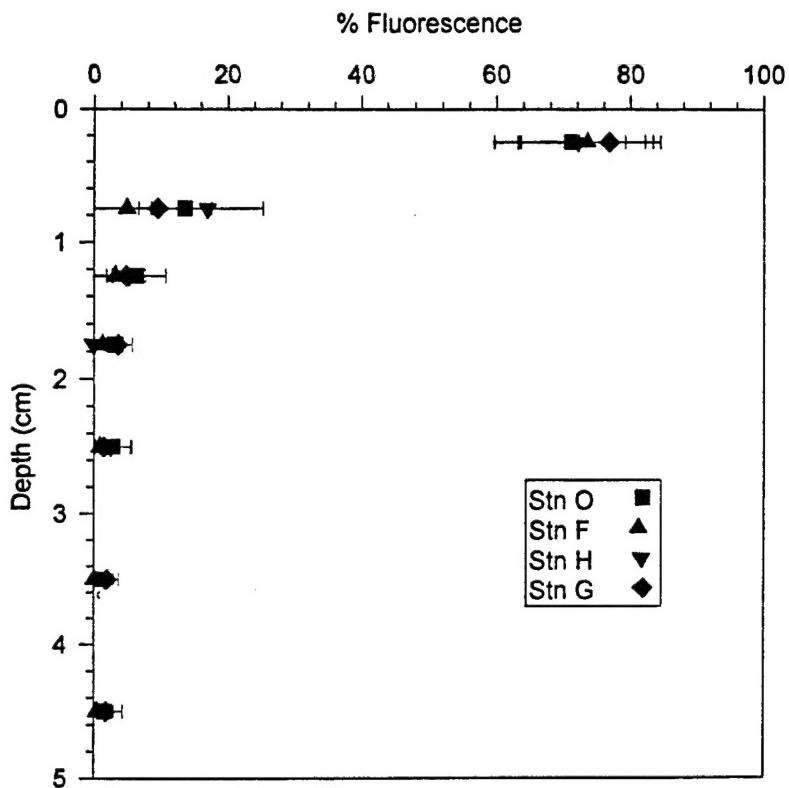


Figure 8. Vertical profiles of percent fluorescence (means and standard deviations) at primary study sites. Values are corrected for background fluorescence. Stations: O = New Tower, F = Old Tower, H = Eckernfoerde Navy Base, G = Mittelgrund.

REPORT DOCUMENTATION PAGE

*Form Approved
OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY <i>(Leave blank)</i>	2. REPORT DATE 1993-1994	3. REPORT TYPE AND DATES COVERED Contract Report	
4. TITLE AND SUBTITLE Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure		5. FUNDING NUMBERS <i>Job Order No.</i> <i>Program Element No.</i> 0601153N <i>Project No.</i> R3103 <i>Task No.</i> <i>Accession No.</i> DN252025	
6. AUTHOR(S) Charles A. Nittrouer and Glenn R. Lopez			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Marine Sciences Research Center State University of New York Stony Brook, NY 11794-500		8. PERFORMING ORGANIZATION REPORT NUMBER NRL/CR/7431--95-0038	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Research Laboratory Marine Geosciences Division Stennis Space Center, MS 39529-5004		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE	
13. ABSTRACT <i>(Maximum 200 words)</i> This document is the final summary report for research conducted under Naval Research Laboratory parent grant N00014-93-1-6004, "Physical and biological mechanisms influencing the development of evolution of sedimentary structure," funded through the Coastal Benthic Boundary Layer Special Research Program during fiscal years 1993-1994. We participated in three cruises in winter and spring 1993, and one in summer 1994; analyses were carried out through 1993 and 1994, and results presented in 1994 and 1995. The description of methods, results, and discussion in this report reflects that chronology.			
14. SUBJECT TERMS Acoustics, Sediments, Mines		15. NUMBER OF PAGES 22	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR